Micro-Cooling Systems Using High Aspect Ratio Microstructures

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Introduction

The control and removal of heat from high power density components, especially where uniform temperatures must be maintained, is a major system physics problem associated with many applications, including heat removal from integrated circuits, precision temperature control in PCR reactors, and prevention of thermal distortion in synchrotron beamline optics. It is particularly challenging to maintain a temperature of <100°C from a system volume $<10^{-3}$ liters with heat transfers of several hundred kilowatts. An example of such an application would be a high-powered diode laser (see figure 1).

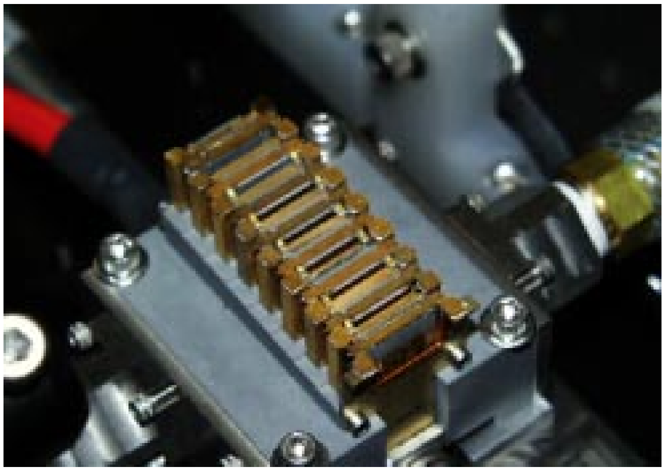

Figure 1 High-powered diode laser array mounted on water-cooled heat exchanger. Picture provided courtesy of Saddleback Aerospace.

The approach that we are applying to the problem of temperature control is cooling using microchannels and microhex cells. These structures (e.g., electronic heat sinks) allow dissipation of heat to the ambient environment through natural convection. The advantages of micro-fabricated elements are surface area-to-volume ratio (see figure 2) and fin densities over one order of magnitude higher than currently available. Further, batch replication would allow large surface area cooling through assembly of an array of modules, and production of these *passive* structures at low cost relative to conventional machining technologies. The hex cell micro-impingement design shown in figure 3 has been proposed by Saddleback Aerospace. The hex-cell is a variation of micro-impingement concepts, where care has been taken to assure that the inlet and outlet paths serve as microchannels as well. As shown in figure 3, the flow enters through the center pipe, impinging upon the inner wall of the faceplate. The flow then turns along the wall, exiting the inner hexagon via grooves etched in the faceplate. When the flow reaches the gap between the inner and outer hexagons it turns away from the faceplate and travels back to the outlet manifold.

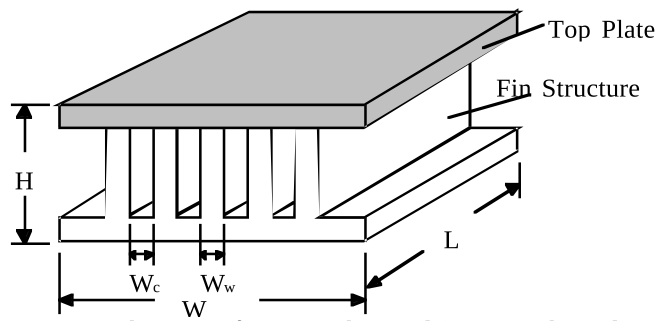

Figure 2: Schematic of Micro-Fabricated (a) Microchannel Heat Exchanger. For L = 1 cm, H = 500µm, W_c = 50µm, and W_w = 50µm, this would result in device which could dissipate over 1000 w/cm^2.

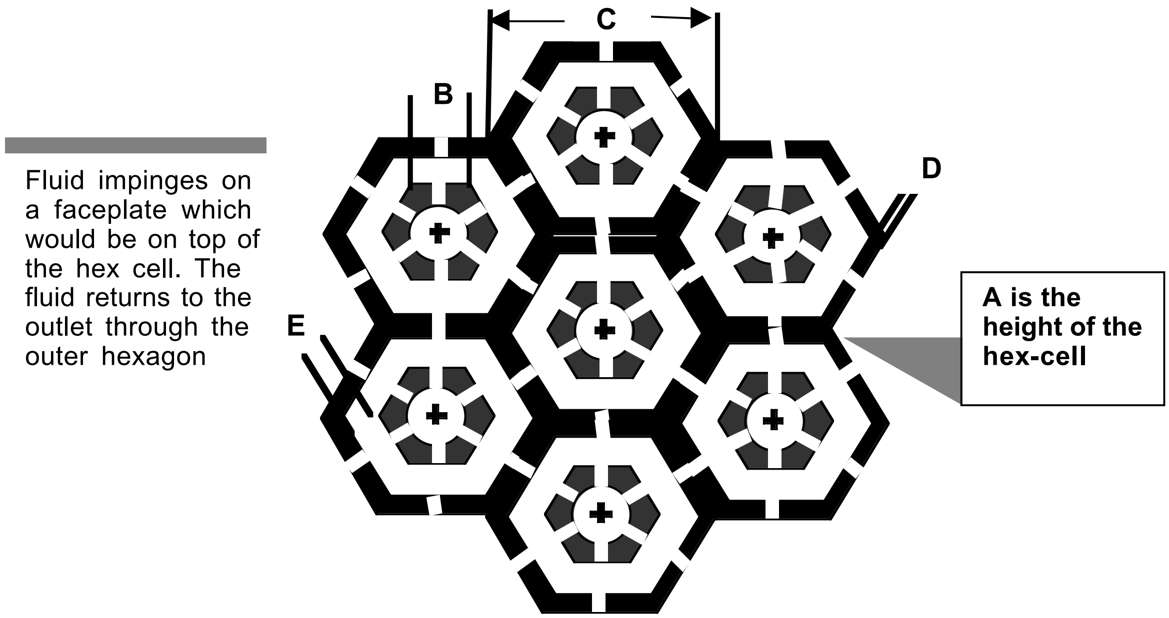

Figure 3: Passive hex cell micro-impingement heat exchanger (partial unit cell). The dimensions are shown in table1.

An optional spire (not shown in figure) extending down the center pipe from the faceplate would serve to provide a microchannel cooling geometry in the inlet, so that more uniform cooling could be provided over the entire face of the cooler. While a detailed thermal model of the Hex-Cell arrangement has not been generated, the hex-cell micro-impingement design offers considerable improvements in thermal performance. The fabrication of this design is somewhat more challenging than the microchannel design in that the faceplate, inlet manifold, outlet manifold and hexagonal layer may have to be fabricated separately and then assembled in a secondary operation. The hexagon layer itself, however, is compatible with the LIGA process and offers excellent thermal performance.

	A (um)	B (um)	C (um)	D (um)	E (um)	ΔP (psi)	R_t (K-cm^2/watt)
With 25um center spire	150	100	200	10	10	15	0.015
Without center spire	150	75	150	10	10	15	0.02

Table 1

Description of the LIGA Fabrication Process

The components for the proposed micro-cooling system will be fabricated using the Lithographie, Galvanoformung, Abformung (LIGA) process. The advantages of LIGA are that (1) LIGA can be applied to a variety of engineering materials, such as polymers and metals, (2) due to the low divergence of the synchrotron source (less than 0.05mrad), high straightness, perpendicularity and surface finish can be achieved, and (3) deep X-ray lithography allows creation of features with aspect ratios above 100:1. LIGA allows parts with characteristic dimensions such as: structure heights of 20-200 microns, minimum feature size of 2 microns, part dimensions of several millimeters and vertical peak-to-valley wall roughness of 30-50 nanometers.

The LIGA process begins with the creation of a chrome-on-quartz photomask from a 2-D CAD layout, similar to that for semiconductor manufacturing. The photomask is then used as a template to generate a 30mm thick (negative) gold pattern on a thinned wafer through photolithography of a spin-cast photoresist layer. The two major performance considerations in mask are to ensure proper exposure ratio between absorbing and transmitting regions of the mask and the profile dimensional accuracy. The LIGA mask is used as a pattern for x-ray exposure onto a polymethyl-methacrylate (PMMA) resist. The X-ray source used for exposures is beamline 3.3.2 (see figure 4). During exposure, the x-ray radiation effectively performs chain scissions on PMMA to reduce the molecular weight in the exposed regions from 10^6 to 10^3 atomic mass units (AMU). The PMMA is then exposed to a chemical developer that selectively dissolves the lower molecular weight polymeric chains. After development of the PMMA resist, the structures formed in the resist can serve as negative patterns for electroforming. Copper is the material of choice for heat exchangers due to its large thermal conductivity.

Figure 4 LIGA Scanner on beamline 3.3.2. The sample to be exposed is inserted through the door in a holder that contains the X-ray mask with the desired pattern, and PMMA resist bonded to a suitable plating base.

Over the last year we have fabricated several microchannel heat exchangers and have begun to develop prototypes of the Hex-cell design (see figure 5). During the next year we plan to complete the Hex-cell work and produce complete heat exchanger assemblies for testing by Saddleback Aerospace. The research partners for this proposed project are LBNL (Materials Science and Engineering Divisions), X-form Inc., and Saddleback Aerospace. The success of this program would influence the design of high-density electronics, diode laser arrays, and biomedical instrumentation. There are a variety of possible application areas: thermal dissipation in radar ground planes, high power analog components, high density integrated circuits, thermal control of high precision optics, and iso-thermal surfaces (medical instrumentation).

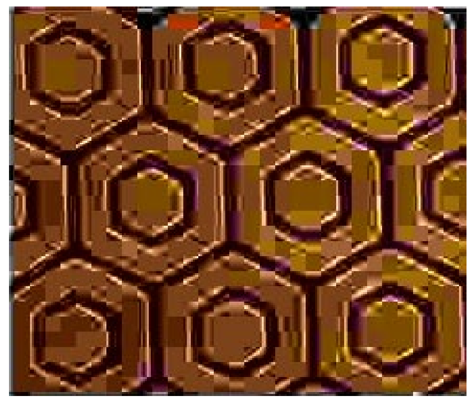

Figure 5 A LIGA Fabricated PMMA mold for a high efficiency heat exchanger, ready for final plating. The channel widths shown are approximately 15 um (spaces) and 60 um for the sides of the hexagon. The each hex cell will stand over 1mm high. In final operation the cooling fluid is pumped through the center and then flows over the sidewall into the return side of cooling loop.

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